

Understanding Energy Consumption and Management in University Buildings: A Sustainability and Socio-Technical Perspective

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Abstract

The built environment accounts for roughly one-third of global energy use, a pattern that carries far-reaching consequences for the natural world, most notably through its contribution to climate change and the progressive depletion of finite resources. This paper aims to raise awareness and deepen understanding of how energy is consumed and should be managed in university buildings, drawing on two complementary theoretical lenses: sustainability theory and socio-technical theory. Methodologically, the paper is grounded in a conceptual narrative review that prioritises constructing reasoned arguments, synthesising scholarly work, and tracing new conceptual linkages, all aimed at generating theoretical insights rather than reporting primary field data. It is openly acknowledged that the absence of original empirical evidence introduces the possibility of interpretive subjectivity. Arguably, the investigation uncovers seven steps ideal for managing energy consumption in university buildings, which include establishing the theoretical foundation underpinning the concepts, recognising energy management as a socio-technical system, mapping stakeholder interactions and motivations, and diagnosing patterns of energy use and identifying hotspots. Additionally, the steps include integrating behavioural change programmes with technological solutions, institutionalising continuous improvement and learning, and fostering a culture of sustainability. The findings attempt to close the gap between academic theorising and day-to-day institutional practice, offering actionable guidance to researchers, facility managers, and university administrators. It is argued that consistent application of this step holds real potential for achieving sustained improvements in energy performance. Nevertheless, the conceptual insights (seven steps) presented in this paper should be tested empirically; future studies are encouraged to collect primary data on the practical effectiveness of sustainability-oriented and socio-technical approaches in real-world university contexts.

Keywords: Energy consumption, energy efficiency, energy management, facility management, socio-technical theory, sustainability theory.

1 Introduction

Rapid urbanisation and continuously rising living standards around the world have placed an unprecedented burden on building energy systems (Lei Liu *et al.*, 2023). Accurately accounting for this demand is complicated by the multifaceted nature of energy infrastructure and the numerous variables that bear on consumption outcomes (Lei Liu *et al.*, 2023). Among the most telling signs of this complexity is the marked shift observed in how building occupants use energy variations that signal a meaningful transformation in everyday consumption behaviour (Lei Liu *et al.*, 2023). These shifts are not benign; their cumulative effect is environmentally significant. The United Nations Environment Programme (UNEP, 2020) has projected that, despite mounting pressure from climate obligations and resource constraints, global energy consumption will continue to rise, potentially reaching 740 million terajoules by 2040. Against this backdrop, many governments have moved to accelerate low-carbon urban transformation

programmes in direct response to urbanisation-driven energy pressures (Zhang, 2023).

The construction and buildings sector is widely regarded as one of the most energy-intensive sector of the global economy, responsible for over 40% of total energy consumption and approximately 35% of worldwide CO₂ emissions (UNEP, 2020). Recognising this, governments and industry bodies in many countries have developed targeted policy instruments and technical frameworks aimed at curbing building energy use. These range from China's Building Energy Conservation and Green Building Development Plan (2021–2025) (Ministry of Housing and Urban-Rural Development, 2022) and its Science and Technology Support to Carbon Peaking Implementation Plan (2022–2030) (National Energy Administration, 2022), to internationally recognised green building rating tools such as BREEAM (United Kingdom), LEED (United States), Green Globes (Canada), NABERS (Australia), SBTool (international), CASBEE (Japan), HQE (France), HK-BEAM (Hong Kong), E-audit (Poland),

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LEnSE (European Union), and Protocollo ITACA (Italy) (Akram *et al.*, 2022). In South Africa, the foundational reference remains the White Paper on Energy Policy (Department of Mineral and Energy, 2005). However, shortcomings in how energy use is assessed within the building sector continue to undermine confidence in the reliability of conservation policies, contributing to resource inefficiency and worsening environmental outcomes (Huo *et al.*, 2018). Robust assessment practices are indispensable for both sound policy formulation and practical energy management (Lei Liu *et al.*, 2023).

2. Literature Review

2.1 Energy consumption in buildings

It is no longer news that global energy consumption has been on the rise, as Lombard, Ortiz, and Pout (2008) and Amasyali and El-Gohary (2018) have noted. This has led to concerns regarding the environmental consequences of energy consumption. The global contribution of buildings to energy consumption, including residential and commercial buildings, has consistently increased, with figures ranging from 20% to 40% in developed countries (Lombard *et al.*, 2008). This is due to the escalating demand for building services and comfort levels, as well as the increase in the amount of time spent indoors. This guarantees that the upward trend in energy demand will persist in the future. The ability to anticipate how buildings will consume energy is of direct practical value, because it allows utility providers, occupants, and facility managers to make better-informed decisions about efficiency improvements, cost control, and resource planning (Okorafor *et al.*, 2019; Anh-Duc *et al.*, 2020). The building sector's position as the single largest contributor to global energy demand and carbon emissions reinforces why a thorough grasp of energy use patterns is foundational to any credible energy and climate policy (Allouhi *et al.*, 2015). This is the reason why it is imperative to comprehend and effectively manage energy consumption at all levels.

2.2 Energy management in university buildings

According to Liu, Cai, and Chen (2026), university buildings are densely populated and have many activities going on. Due to the heterogeneous behaviour of humans, such diversity greatly impacts occupant behaviour and electricity consumption. As key institutions in any nation and significant energy consumers, universities have a critical responsibility to lead efforts in energy efficiency and renewable energy use to reduce their environmental impact (Türle and Celen, 2026). In this context, a study carried out by Türle and Celen (2026) at Gümüşhane University building has identified the sources of greenhouse gas emissions and provides the opportunity to track, measure, and suggest reduction strategies in the years to come. These results suggest that universities need to

focus on their energy consumption patterns to reduce their carbon emissions, for example, by placing greater emphasis on renewable energy sources, energy efficiency, and balanced consumption (Guo *et al.*, 2018; Killian and Kozek, 2016; Türle and Celen, 2026). Arguably, there is extant research on energy consumption and management in South African university building.

2.3 Energy Consumption Prediction Patterns

Forecasting building energy use is particularly valuable during the operational and maintenance phases of a building's life cycle, where accurate data can drive meaningful improvements in performance (Anh-Duc *et al.*, 2020). Broadly speaking, two analytical traditions have emerged for this purpose: physics-based simulation and data-driven modelling (Amasyali and El-Gohary, 2018). Physics-based tools including DOE-2 and EnergyPlu work by modelling the thermodynamic properties of building components, HVAC configurations, internal loads, and meteorological conditions in detail (Anh-Duc *et al.*, 2020). Their primary limitation is that they demand substantial, often unavailable input data and are ill-suited for rapid or large-scale analyses, particularly when extending to city or national scale assessments (Amasyali and El-Gohary, 2018; Anh-Duc *et al.*, 2020).

Data-driven approaches offer a contrasting advantage: they derive predictions from historical energy records, and their practical relevance has grown considerably alongside advances in AI and the Internet of Things (Anh-Duc *et al.*, 2020; Lei Liu *et al.*, 2023). Open data availability is central to their effective deployment. Numerous ML-based prediction frameworks have been developed and applied in building energy research, including artificial neural networks (ANNs) (Qiao and Liu, 2020), decision trees (Killian and Kozek, 2016), adaptive neuro-fuzzy inference systems (ANFIS) (Xie *et al.*, 2019), and support vector machines (SVM) (Wu *et al.*, 2007).

Reducing energy consumption through smarter and more efficient use carries a triple dividend: it brings down costs, cuts carbon emissions, and strengthens energy security (McNeil *et al.*, 2019). A quantitative method was also proposed to assess how building greening interventions affect overall energy use, providing a decision-support tool for urban policy implementation (Qiao and Liu, 2020). Yet the complexity of evaluating energy use at urban or national scales largely because of the layered interdependencies within building systems remains a persistent challenge (Huo *et al.*, 2022).

Three broad methodological categories are commonly used to assess building energy consumption: top-down, bottom-up, and hybrid modelling approaches (Lei Liu *et al.*, 2023). Top-down approaches treat an entire building stock as a single unit, estimating consumption

by reference to macroscopic variables such as climate conditions, population density, and the morphology of the urban environment (Huo *et al.*, 2022; Zhang *et al.*, 2021; Zhou *et al.*, 2023). In contrast, bottom-up approaches disaggregate consumption by examining individual building characteristics and aggregating detailed sub-system data (Howard *et al.*, 2012; Huo *et al.*, 2019; Wang *et al.*, 2020). Guo's (2020) EBEC-China model exemplifies this approach, showing that re-estimated national consumption figures derived from bottom-up methods can deviate from top-down estimates by between 10% and 36%.

While both approaches have seen widespread application, each carries inherent weaknesses including ambiguous assessment criteria and opaque internal causal structures (Huo *et al.*, 2022; Guo, 2020). Hybrid models have been proposed as a remedy, drawing variously on behaviour based energy economy frameworks (Rivers and Jaccard, 2005), integrated multi-commodity price formulations (Böhringer and Rutherford, 2006), and combined benchmarking strategies that blend top-down indicators with bottom-up reference values (Hollberg *et al.*, 2019). Though promising, hybrid models have not fully resolved the problem of internal complexity or overcome the constraints of static assessment methodologies (Lei Liu *et al.*, 2023). Ocampo Batlle *et al.* (2020) demonstrated the potential of energy baseline and performance indicator frameworks in an educational building context, finding potential annual savings of up to 9.6%. Building on these observations, the present paper aims to advance a logical, theory-grounded argument that identifies and deepens the understanding of energy consumption and management dynamics in university buildings through a coherent, step-by-step guide.

2.4 Adopted theory of the study

Sustainability theory, as Childers *et al.* (2014) note, resists a single fixed definition but tends to coalesce around human needs, values, and the interests of future generations themes that echo the foundational formulation in the Brundtland Report (1987). At its core, this theory insists on resource efficiency as the

into focus the interplay between social dynamics and technical systems. Okorafor (2019) has previously drawn attention to the disconnect that often exists between these two dimensions in building retrofit and management efforts a gap that Swan and Brown (2013) characterise as a structural feature of a fundamentally socio-technical problem, one that cannot be resolved by engineering alone but requires coordinated expertise drawn from across industrial, technical, and social domains.

Ma *et al.* (2012) add texture to this view by identifying the range of socio-technical factors at stake: retrofit technologies, occupant behaviour, building-specific parameters, client expectations, and unpredictable environmental influences. Authors such as Natural Resources Canada (2015) have further argued that one of the most persistent barriers to long-term energy management planning is the challenge of accounting for how building occupants behave. Fulford (2011) captured this succinctly, observing that behavioural change while invisible in engineering terms can be decisive in determining whether an energy management initiative succeeds or fails. Karvonen (2013) reinforces the point: achieving meaningful reductions in energy demand depends on integrating changes in how stakeholders understand, perceive, and practise energy use alongside physical and technical interventions. Taken together, these perspectives lead to the conclusion that any effective intervention in university building energy management must be simultaneously grounded in sustainability theory and attuned to socio-technical realities. Despite this, current energy efficiency measures in public buildings have generally failed to give sufficient weight to these dimensions (Okorafor, 2019). Addressing this gap calls for developing a richer understanding of the variables involved in energy efficiency initiatives, the dynamics that govern their interaction, and the relationships between them that either enable or obstruct effective management. The research gap identified in this literature the missing bridge between social and technical dimensions of energy management is illustrated in Figure 1.

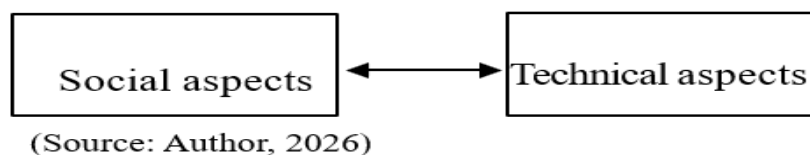


Figure 1: The missing link between the social and technical aspects of energy consumption and management

mechanism for meeting present demands without foreclosing the options of those who come after. Within universities, sustainability extends beyond straightforward energy conservation; it involves embedding sustainability as a fundamental dimension of organisational culture and institutional operations. The socio-technical theory, on the other hand, brings

The mechanisms through which sustainability and socio-technical integration produce effective energy management in university buildings remain underspecified in the existing literature. This study positions itself within that gap, seeking to advance understanding of the phenomenon through a socio-technical and sustainability-informed lens and, in

practical terms, to propose a structured, step-by-step guide for achieving optimal energy consumption and management outcomes in university buildings.

3. Research Methodology

This study is anchored in a conceptual narrative literature review methodology informed by sustainability theory and socio-technical theory. Rather than generating new empirical data, the approach is oriented toward constructing rigorous theoretical and logical arguments, consolidating and synthesising existing scholarship. The methodology serves as the scaffolding for the conceptual understanding and findings of the paper.

4. Findings and Discussion

4.1 A Conceptual Guide for Optimal Energy Consumption and Management

The following seven steps are guided around the theoretical foundations outlined above (see section 2.4), with each step grounded in explicit logical reasoning and reviews from scholarly articles.

Step 1: Recognising energy consumption and management through sustainability and socio-technical lenses

Universities like other corporate entities should no longer treat sustainability as an optional or peripheral concern (Lozano *et al.*, 2015). Corporate sustainability, in its contemporary form, involves the deliberate balancing of economic performance, environmental responsibility, and social accountability across both present and future time horizons (Lozano *et al.*, 2015). This means that universities should not base their decisions about energy consumption and management solely on cost considerations. Institutional decision-making must factor in environmental impacts, including CO₂ emissions, resource depletion, and ecosystem effects, from the outset. This orientation aligns with the core logic of sustainability theory, which demands that resource management decisions account for long-term consequences and embed a sense of obligation toward future generations. Energy management, framed this way, becomes an exercise in environmental stewardship as much as an operational or financial concern.

Step 2: Recognise Energy Management as a Socio-Technical System

Energy management is the process of planning, monitoring and controlling the use of energy to ensure it is used efficiently, cost-effectively and sustainably. Energy consumption and management have moved to the centre of organisational life in virtually every sector, and this centrality has grown in direct proportion to the urgency of CO₂ reduction commitments (Christina *et al.*, 2015). Adopting a socio-technical systems lens means recognising that energy

performance is not purely a technical outcome; it emerges from the interaction between physical infrastructure and the people who use, govern, and maintain it. This involves understanding the interdependencies between technological systems (tools, equipment, sensors), organisational processes and work patterns, and institutional culture (Christina *et al.*, 2015; Swan and Brown, 2013). In practical terms, a university building should be understood as a living socio-technical system: one in which students, staff, and visitors co-exist with policies, schedules, building management systems, and physical infrastructure all of which influence one another continuously. The interrelationship between user behaviour and technical infrastructure is not incidental but constitutive of energy outcomes (Karvonen, 2013). The key constructs at this level are occupant behaviour, regulatory mechanisms, and technological enablers.

Step 3: Map Stakeholder Interactions and Motivations

Within any university, different constituents such as; students, academic staff, administrative staff, facilities managers, cleaners, maintenance contractors, university leadership and visitors approach energy use with different levels of awareness, different motivations, and different degrees of agency (Li and Zeng, 2024). Managing this diversity requires that institutions move beyond uniform communication strategies and instead develop a clear picture of who the relevant stakeholders are, what drives their behaviour, and how their interests can be aligned with broader energy management objectives. Koshman and Ulyanova (2014) have argued that human beings are not passive elements in an energy management system they are integral participants whose motivations and actions shape system performance. Karvonen (2013) extends this logic by suggesting that meaningful progress in energy management is often achieved not through blanket measures but through facilitated engagement between occupants, housing or facilities providers, and technical professionals engagement that produces solutions sensitive to the particular circumstances of each context. The author of this paper argues that constructing a stakeholder map one that captures each group's incentive structure and identifies potential points of alignment and conflict is a prerequisite for the kind of coordinated governance that sustainable energy management demands. The key constructs here are stakeholder engagement, incentive alignment, and participatory governance. This entails involving all individuals and organizations affected by energy policies and decisions by ensuring that stakeholders share common energy management goals through rewards and policies. This approach enables stakeholders to actively participate in the planning, policy formulation, implementation, and monitoring of energy-related activities.

Step 4: Diagnose Patterns of Energy Use and Identify Hotspots

Identifying energy hotspots in university buildings aims to pinpoint systems or activities exhibiting significant energy usage. This hotspot might be laboratories, libraries, lecture halls, residences, HVAC-intensive buildings and computer labs. The indicators that can be used include kWh/m²/year, peak load, occupancy-adjusted energy use, and equipment-level consumption. Identifying these hotspots is essential for enhancing energy efficiency. Energy-saving behaviour in higher education institutions is crucial not only for immediate financial gains but also for the broader societal goal of achieving a low-carbon transition (Li and Zeng, 2024). Implementing those objectives in institutional practice demands more than aspirational policy; it involves contextual specificity. Li and Zeng (2024) have identified a specific need for customised strategies that might foster genuine energy-conscious habits within university communities. The author asserts that targeted and effective intervention commences with a comprehensive understanding of the specific contexts, timings, and methods of energy use (Pandit et al., 2023). In the absence of diagnostic clarity, interventions may become generic and inadequately aligned with the actual energy consumption patterns of a specific building or campus. Energy audits, sub-metering, and occupancy monitoring are instruments used for this aim, and their results form the foundation for crafting remedies that are specifically tailored rather than indiscriminately adopted from other contexts.

Step 5: Integrate Behavioural Change Programmes with Technological Solutions

Consequently, behavioural change initiatives such as switch-off campaigns, energy dashboards, feedback systems, incentives, training and student-led initiatives can be integrated with technology solutions such as smart meters, occupancy sensors, LED retrofits, building management systems and HVAC optimisation. This step sits at the heart of the socio-technical approach. A notable consensus exists in the literature exemplified by the positions of Natural Resources Canada (2015), Fulford (2011), and Karvonen (2013) that behavioural dimensions are among the most consequential and most frequently underestimated aspects of energy management. The inability to address occupant behaviour consistently is identified as a major structural barrier to the realisation of energy management plans. Fulford (2011) makes the provocative point that behavioural change though it produces no hardware, installs no sensor, and draws no engineering diagram can determine the ultimate success or failure of a management initiative. Natural Resources Canada (2015) goes further, characterising energy management as fundamentally a change management challenge, with technical interventions as necessary but not sufficient conditions for success. Karvonen (2013) captures the integrative logic well:

reducing energy demand over time requires changing not only physical systems but also the habits, perceptions, and motivational frameworks of the people who use them. Technological solutions and behavioural programmes should therefore not be designed in parallel silos but as mutually reinforcing components of a single integrated strategy.

Step 6: Institutionalise Continuous Improvement and Learning

Energy management cannot be treated as a problem to be solved once and then set aside. Gallo and Capozzoli (2024) stress that effective energy governance must be dynamic, capable of responding to changing conditions, emerging data, and the evolving nature of institutional needs. This requires universities to embed practices of monitoring, reporting, and evaluation into their management routines, not as an administrative burden but as the engine of an ongoing learning process (Dahiya and Laishram, 2024). Regularly reviewing and acting upon performance data enables institutions to cultivate the adaptive capacity necessary for transforming positive intentions into sustainable energy outcomes. Over time, this process cultivates a community of practice, a social structure built on shared knowledge, collective learning, and the willingness to adjust approaches in response to evidence. The key constructs at this stage are knowledge-sharing mechanisms, adaptive management, and organizational learning. Knowledge-sharing mechanisms, as confirmed by Gluch, Johansson, and Räisänen (2013), enhance energy information dissemination among university building stakeholders through training workshops, awareness campaigns, online platforms, and research collaborations. This approach fosters better energy efficiency and sustainability. Adaptive management, which involves modifying strategies based on monitoring and feedback, allows for adjustments in energy management in response to changing conditions and includes regular energy performance assessments and updates to energy-saving measures (Gluch et al., 2013), whereas organizational learning enhances energy management by using past experiences and data analysis to drive continuous improvement, such as reviewing energy audits and utility consumption data.

Step 7: Foster a Culture of Sustainability

Ultimately, sustained improvement in energy performance depends on more than policies and procedures; it requires that sustainability become a living part of institutional identity (Worts, 2006). Cotton and Winter (2026) argue that embedding sustainability into a university's values and day-to-day operations is the most reliable way to ensure that the commitment endures beyond individual leadership cycles or specific initiatives. The author contends that this cultural embedding can be achieved through a combination of three mutually reinforcing strategies: integrating energy and sustainability themes into the

academic curriculum; demonstrating visible institutional commitment through the decisions and public communications of senior leadership; and cultivating community ownership through student-led projects, green societies, and grassroots campus initiatives. When sustainability becomes genuinely embedded in institutional identity, it shifts from being an external requirement to being an internal norm shaping how people think, communicate, and act in ways that make energy efficiency a shared and self-reinforcing aspiration (Cotton and Winter, 2026; Worts, 2006). The key constructs here are sustainability education, leadership commitment, and community participation. Arguably, sustainability education should be part of the university's energy management that teaches responsible energy use and environmental protection through campaigns, workshops, and inclusion in the curriculum, as Dyer and Dyer (2017) espoused. The aim is to encourage energy-saving habits among students and staff. Furthermore, leadership commitment is critical, as university management should actively champion energy policies, resource allocation, and stakeholder engagement to place sustainability goals at the forefront. Involvement of the community increases the feeling of shared responsibility through activities like sustainability clubs and public consultations, which helps increase awareness and collaboration in energy management efforts (Dyer and Dyer, 2017).

5. Conclusion and Further Research

This paper has been developed using a conceptual narrative review shaped by sustainability theory and socio-technical principles applied to the challenge of understanding and improving energy consumption and management in university buildings. The conceptual contribution takes the form of a seven-step design to

guide institutional thinking and practice moving away from fragmented or purely engineering-driven responses toward a holistic, integrated approach that recognizes people, technology, policy, and culture as interdependent dimensions of the energy management challenge. These steps vis-à-vis are a theoretical foundation underpinning the concepts, recognizing energy management as a sociotechnical system, mapping stakeholder interactions and motivations, diagnosing patterns of energy use and identifying hotspots, integrating behavioural change programs with technological solutions, institutionalizing continuous improvement and learning; and fostering a culture of sustainability. The argument advanced here is that this kind of sustainability-oriented and socio-technically informed approach is not merely desirable but necessary for achieving the depth and durability of improvement that universities need. Consistent and purposeful application of the proposed steps has the potential to generate meaningful gains in energy performance. However, the conceptual nature of this study carries inherent limitations such as no primary data, no empirical validation, possible author subjectivity, limited methodological transparency, and limited context-specific evidence. Empirical research is now required to test and refine these propositions in practice, particularly empirical studies using case studies, surveys, energy audits, or intervention-based evaluation.

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